

A Population Explosion: The Nature and Evolution of X-ray Binaries in Diverse Environments
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Enigmatic sub-luminous accreting neutron stars in our Galaxy

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Abstract. During the last few years a class of enigmatic sub-luminous accreting neutron stars has been found in our Galaxy. They have peak X-ray luminosities (2–10 keV) of a few times 10^{34} erg s $^{-1}$ to a few times 10^{35} erg s $^{-1}$, and both persistent and transient sources have been found. I present a short overview of our knowledge of these systems and what we can learn from them.

1. Sub-luminous accreting neutron stars in low-mass X-ray binaries

Instrumental limitations (e.g., sensitivity, spatial resolution) of past X-ray instruments restricted the study of accreting neutron stars in low-mass X-ray binaries to the relatively bright systems, with 2–10 keV X-ray luminosities of 10^{36-38} erg s $^{-1}$. The existence of fainter sources was well known, but until recently they could not be studied in detail. Luckily, this is not true for the current X-ray satellites and a sizable number (~ 15) of sub-luminous (X-ray luminosities of 10^{34-35} erg s $^{-1}$) accreting neutron stars have been found in the last few years (called sub-luminous NS LMXBs; I will only consider the systems in which the companion is suspected to have a low mass [$< 1 M_{\odot}$] but there exist also a population of systems which have a suspected high-mass companion). Their neutron star nature has been confirmed by the detection of type-I X-ray bursts. Two of them are persistent sources, while the others are transients with a large variety in outburst durations and recurrence times.

The persistent sub-luminous NS LMXBs: Currently, two such sources are known: 1RXS J171824.2–402934 (Voges et al. 1999; Kaptein et al. 2000) was shown to be persistent with a 0.5–10 keV X-ray luminosity of only $\sim 5 \times 10^{34}$ erg s $^{-1}$ by In 't Zand et al. (2005). After AX J1754.2–2754 (Sakano et al. 2002; Chelovekov & Grebenev 2007) exhibited a type-I X-ray burst, Del Santo et al. (2007a) detected it with Swift at a 2–10 keV luminosity of a few times 10^{34} erg s $^{-1}$ establishing it too as a persistent sub-luminous NS LMXB.

The quasi-persistent sources: Recently, two quasi-persistent (outburst durations of years) sub-luminous NS LMXBs have been identified. The best example is XMMU J174716.1–281048 (Sidoli & Mereghetti 2003). Brandt et al. (2006), using INTEGRAL, reported on a new type-I X-ray burster near the Galactic center which was very soon identified with XMMU J174716.1–281048 (Wijnands 2006). After analyzing the burst properties and several XMM-Newton observations, Del Santo et al. (2007b) identified the source as a quasi-persistent sub-luminous NS LMXB with a luminosity of $\sim 5 \times 10^{34}$ erg s $^{-1}$; a classification which was later confirmed by a series of Swift and Chandra observation of the source in 2007 (Degenaar & Wijnands 2007; Degenaar et al. 2007; Sidoli et al. 2007).

Maeda et al. (1996) first discovered the second system, AX J1745.6–2901, as a bursting transient near Sgr A*, with a luminosity of a few times 10^{35} erg s $^{-1}$ and with deep eclipses every ~ 8.4 hours (the orbital period). They suggested that AX J1745.6–2901 could be the

old, bright transient A 1742–289 (albeit this time in a faint outburst), but Kennea & Skinner (1996) could not find eclipses in the Ariel V data of A 1742–289 indicating that AX J1745.6–2901 is a new transient sub-luminous NS LMXB. Quasi-daily observations of the Galactic center with Swift in February 2006 yielded a new transient, Swift J174535.5–290135.6 (Kennea et al. 2006), which XMM-Newton conclusively identified with AX J1745.6–2901 (showing eclipses with the right period; Porquet et al. 2007). The source turned off after staying on for several months (Degenaar & Wijnands 2008), but it was detected in outburst again in February 2007 (Kuulkers et al. 2007; Wijnands et al. 2007). The Swift quasi-daily monitoring campaign continued also in 2007 showing that the source remained active throughout 2007 (Degenaar & Wijnands 2008).

The transient sources: In addition, about a dozen, short-duration, transient sub-luminous NS LMXBs are known (see, e.g., Wijnands et al. 2006). In general, they have peak outburst luminosities (2–10 keV) of 10^{34-35} erg s^{−1} and their outbursts last from a few days to at most a few weeks. The combination of their very-faint peak luminosity and their transient nature makes them difficult to discover and study, but dedicated programs (e.g., Wijnands et al. 2006) are increasing the number of these systems known and our understanding of them.

2. What can we learn from them

The total number of sub-luminous NS LMXBs in our Galaxy is unknown. That they are found in ever growing numbers despite the difficulties in observing them suggests that they might be quite abundant. Binary evolution and population synthesis models might need modifications to explain their properties (e.g., unusual binary configuration, see e.g., In ’t Zand et al. 2005) and their number density in our Galaxy. Also, these systems may help us understand the effects of accretion on super-dense neutron-star matter as I explain below.

Accreting millisecond X-ray pulsars: It is thought that NS LMXBs are the progenitors of the millisecond radio pulsars, thus, accreting systems must also harbor a fast spinning neutron star. The 9 known accreting millisecond X-ray pulsars (AMXPs; excluding Aql X-1 whose pulsations are not conclusively accretion driven; Casella et al. 2007) confirm this hypothesis but the question remains: why are the other systems not AMXPs? It has been suggested that in the non-pulsating systems the neutron-star magnetic field could be temporarily buried by the accreted matter. When the accretion phase ends, the field reemerges from the crust and the systems become millisecond radio pulsars. If the time-averaged mass accretion rate $\langle \dot{M} \rangle$ of the accretors is relatively high, the accreted matter can bury the field throughout the life of the X-ray binary making it impossible to see pulsations. However, if $\langle \dot{M} \rangle$ is low enough for the field to diffuse out of the accreted matter faster than it is buried then these systems will exhibit pulsations (e.g., Cumming et al. 2001). The exact processes behind field-burying depend on the properties of the neutron-star crust, which in turn depend on the equation of state of neutron-star matter and how the accreted matter burns on the surface of the star (determining the composition of the crust). Seven of the known AMXPs have indeed among the lowest $\langle \dot{M} \rangle$ of the relatively bright transients (Fig. 1, left), pointing to the importance of $\langle \dot{M} \rangle$ in this process. Two systems have higher $\langle \dot{M} \rangle$ (resembling that of the non-pulsating systems) but their pulsations were intermittent and possibly triggered by bright X-ray flashes (Galloway et al. 2007; Altamirano et al. 2007) which might have disturbed the screening currents in the crust, temporarily letting the field out before it

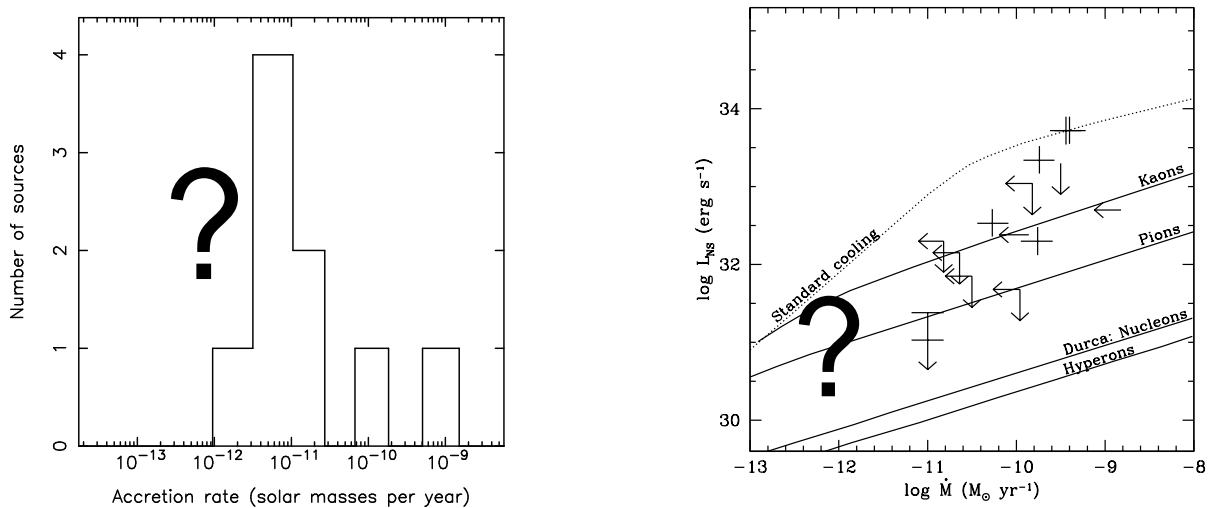


Figure 1. Left: the number of AMXPs versus $\langle \dot{M} \rangle$ (excluding Aql X-1; after Galloway 2006). Right: luminosities of quiescent neutron-star transients versus $\langle \dot{M} \rangle$ (after Heinke et al. 2007). Question marks indicate where the sub-luminous NS transients are expected.

was buried again by the accreted matter. This also suggests that field-burying is relevant in understanding the presence or absence of pulsations in neutron-star accretors.

Unfortunately, firm conclusions are not possible with only 9 AMXPs. Luckily, the sub-luminous NS LMXB can help because they have similar (the persistent sources) or even lower $\langle \dot{M} \rangle$ (the transients). If truly all neutron stars have an intrinsic magnetic field and this field is indeed buried in the non-pulsating systems, then the sub-luminous NS LMXBs should also be visible as AMXPs because their field cannot be buried. If most sub-luminous NS LMXBs are found to be AMXPs the field-burying scenario is strengthened, plus, a larger number of AMXPs enable more detailed comparative studies between pulsating and non-pulsating systems to elucidate the field-burying physics and provide new insights into the behavior of matter and magnetic fields under extreme conditions. But if only sporadically an AMXP is found, then a mechanism other than field-burying is responsible for preventing observable pulsations for most NS LMXBs, and we are back to the drawing board!

Thermonuclear flashes: The properties of type-I X-ray bursts (rise and decay times, energetics, recurrence times) depend strongly on the characteristics of the neutron star (i.e., in the crust) and the chemical composition of burning material. The latter can change drastically as the \dot{M} onto the neutron star varies, defining several burning regimes which lead to different types of flashes (see Fujimoto et al. 1981; Bildsten 1998). Although the exact \dot{M} range for each regime depends on the specifics of the X-ray flash model used and on the assumed properties of the neutron star (e.g., crust microphysics, compactness, core temperature), most models roughly agree on the values of these limits. However, observationally, some sources fit the predictions while others deviate significantly (see review of Strohmayer & Bildsten 2006). Nevertheless, a study of ~ 1000 flashes from many sources using the RXTE archive clearly established that the great majority of sources behave consistently with the theoretical \dot{M} limits (Galloway et al. 2006). Thus, although the details of the physics behind flashes still elude us, the global behavior is reasonably well understood.

Unfortunately, this is really only true for the relatively fast accretors ($\dot{M} > 10^{-10} M_{\odot} \text{ yr}^{-1}$). Most of the flashes reported by Galloway et al. (2006) occurred when the neutron stars were accreting at high rates, and while this study found that the flashes observed in the lowest \dot{M} regime behaved as predicted, most of the flashes observed at the lowest \dot{M} come from one particular source (EXO 0748–676) and firm conclusions cannot be drawn. Similar results were reported for a few other sources (Cornelisse et al. 2002; In ’t Zand et al. 2005), but several other systems (not studied by Galloway et al. 2006, because RXTE did not observe them) are not consistent with this picture (Cornelisse et al. 2002). Recently, Peng et al. (2007) suggested an explanation: when the \dot{M} is very low, the helium and CNO elements in the accreted matter sediment out of the accreted fuel before it reaches the conditions at which hydrogen ignites resulting in different flash behavior; when \dot{M} is high sedimentation is not important (see also Cooper & Narayan 2007). The limited observational data precludes detailed testing of this scenario, and this model does not explain the differences between the sources. Clearly, studying type-I bursts from sub-luminous NS LMXBs will help us understand burst physics and neutron-star reacts to the accretion of matter.

Cooling neutron stars: The transient NS LMXBs are also interesting when in their quiescent state, in which they are expected to emit thermal surface radiation because the accreted matter heats the star during the outburst (Brown et al. 1998). The amount of radiation depends on $\langle \dot{M} \rangle$ and on the core cooling processes. The latter depend strongly on the core composition; exotic matter (e.g., kaon/pion condensates, hyperons, unbound quarks) would cool the core much faster than if it was not present (see review by Yakovlev & Pethick 2004) and the curves in Fig. 1, right). By combining the observed emission with estimates of $\langle \dot{M} \rangle$, the core properties and thus the behavior of ultra-dense matter can be probed. Until now all studies involved transients with $\langle \dot{M} \rangle \geq 10^{-11} M_{\odot} \text{ yr}^{-1}$, which showed that several of them have relatively hot neutron stars which cool down without enhanced cooling, but a large number have cores colder than expected if only standard core cooling occurs (Brown et al. 1998, Fig. 1, right). Such a cold core might result because enough matter was accreted onto the star to increase its mass and core density to the point where enhanced core cooling processes can occur (Brown et al. 1998; Colpi et al. 2001; Yakovlev & Pethick 2004).

So far, the sub-luminous NS LMXBs with $\langle \dot{M} \rangle \approx 10^{-12} M_{\odot} \text{ yr}^{-1}$ have not been studied in detail in quiescence, thus, it is unclear what to expect from their quiescent thermal emission. If their current levels of $\langle \dot{M} \rangle$ are representative of their whole accretion life (possible if they have primordial brown dwarf or even planetary companions, King & Wijnands 2006) then they could not have accreted enough matter to raise the core density above the threshold for fast cooling processes (assuming all neutron stars are born with roughly similar masses) and they should follow the ‘standard cooling’ curve in Figure 1 (right) and have thermal emission easily detectable with Chandra or XMM-Newton. Confirming this observationally would reaffirm the cooling models, falsifying it could imply that fast cooling is also possible at moderate central densities, or, more likely, that these systems may have accreted in the past at levels higher than we observe now thereby accreting enough matter to allow for enhanced core cooling processes. Detailed binary evolution studies are needed to be conclusive.

Intriguingly, there is a class of sources which can significantly contribute to core cooling studies in accreting neutron stars: low-luminosity neutron-star X-ray sources in Galactic globular clusters. More than a hundred have been identified as neutron-star transients in their quiescent states with Chandra and XMM-Newton (Heinke et al. 2003; Pooley et al. 2003; Webb et al. 2006) based on their X-ray luminosities and thermal spectral shape. This identification must still be confirmed (i.e., by observing accretion outbursts), but it is likely to be correct since no other known X-ray sources have these properties and they are too

abundant to be a previously unknown object type. Thus, we know their quiescent luminosities accurately, but not their $\langle \dot{M} \rangle$ because no accretion outbursts have been observed from them. Using the limits on both peak outburst luminosities and recurrence time provided by monitoring X-ray instruments and the many sensitive pointed X-ray observations of the Galactic globular clusters, I estimate an averaged $\langle \dot{M} \rangle$ for these systems of typically $10^{-12} M_{\odot} \text{ yr}^{-1}$ or less, precisely in the range of the sub-luminous NS LMXBs. Plotting this $\langle \dot{M} \rangle$ in Figure 1 (right) with the measured quiescent luminosities, these systems can only be explained if standard core cooling alone occurs in their cores. Sensitive monitoring observations of a large number of globular cluster systems should be performed to catch the expected very-faint X-ray outbursts which would conclusively establish them as NS LMXBs.

References

- Altamirano, D., et al. 2008, ApJL in press, ArXiv e-prints, 708, arXiv:0708.1316
 Bildsten, L. 1998, NATO ASIC Proc. 515: The Many Faces of Neutron Stars., 419
 Brandt, S., et al. 2006, The Astronomer's Telegram, 970
 Brown, E. F., Bildsten, L., & Rutledge, R. E. 1998, ApJ, 504, L95
 Casella, P., et al. ApJL in press, ArXiv e-prints, 708, arXiv:0708.1110
 Chelovekov, I. V., & Grebenev, S. A. 2007, The Astronomer's Telegram, 1094
 Colpi, M., Geppert, U., Page, D., & Possenti, A. 2001, ApJ, 548, L175
 Cornelisse, R., et al. 2002, A&A, 392, 885
 Cooper, R. L., & Narayan, R. 2007, ApJ, 661, 468
 Cumming, A., Zweibel, E., & Bildsten, L. 2001, ApJ, 557, 958
 Degenaar, N., et al. 2007, The Astronomer's Telegram, 1136
 Degenaar, N., & Wijnands, R. 2007, The Astronomer's Telegram, 1078
 Degenaar, N., & Wijnands, R. 2008, MNRAS, in preparation.
 Del Santo, M., Romano, P., Sidoli, L., & Bazzano, A. 2007a, The Astronomer's Telegram, 1143
 Del Santo, M., et al. 2007b, A&A, 468, L17
 Fujimoto, M. Y., Hanawa, T., & Miyaji, S. 1981, ApJ, 247, 267
 Galloway, D. K. 2006, The Transient Milky Way: A Perspective for MIRAX, 840, 50
 Galloway, D. K. et al. 2006, ApJ, submitted, ArXiv Astrophysics e-prints, arXiv:astro-ph/0608259
 Galloway, D. K., et al. 2007, ApJ, 654, L73
 Heinke, C. O., et al. 2003, ApJ, 598, 501
 Heinke, C. O., Jonker, P. G., Wijnands, R., & Taam, R. E. 2007, ApJ, 660, 1424
 in't Zand, J. J. M., Cornelisse, R., & Méndez, M. 2005, A&A, 440, 287
 Kaptein, R. G., et al. 2000, A&A, 358, L71
 Kennea, J. A., & Skinner, G. K. 1996, PASJ, 48, L117
 Kennea, J. A., et al. 2006, The Astronomer's Telegram, 753
 King, A. R., & Wijnands, R. 2006, MNRAS, 366, L31
 Kuulkers, E., et al. 2007a, A&A, 466, 595
 Kuulkers, E., et al. 2007b, The Astronomer's Telegram, 1005
 Maeda, Y., Koyama, K., Sakano, M., Takeshima, T., & Yamauchi, S. 1996, PASJ, 48, 417
 Peng, F., Brown, E. F., & Truran, J. W. 2007, ApJ, 654, 1022
 Pooley, D., et al. 2003, ApJ, 591, L131
 Porquet, D., et al. 2007, The Astronomer's Telegram, 1058
 Sakano, M., Koyama, K., Murakami, H., Maeda, Y., & Yamauchi, S. 2002, ApJS, 138, 19
 Sidoli, L., & Mereghetti, S. 2003, The Astronomer's Telegram, 147
 Sidoli, L., Romano, P., Mereghetti, S., & Santo, M. D. 2007, The Astronomer's Telegram, 1174
 Strohmayer, T., & Bildsten, L. 2006, Compact stellar X-ray sources, 113
 Voges, W., et al. 1999, A&A, 349, 389
 Webb, N. A., Barret, D., & Gendre, B. 2006, Advances in Space Research, 38, 2930

Wijnands, R. 2006, The Astronomer's Telegram, 972

Wijnands, R., et al. 2006b, A&A, 449, 1117

Wijnands, R., et al. 2007, The Astronomer's Telegram, 1006

Yakovlev, D. G., & Pethick, C. J. 2004, ARA&A, 42, 169